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PERFORMANCE EVALUATION OF WASTE GLASS POWDER IN AMBIENT-CURED GEOPOLYMER CONCRETE

Fatima Muzaffar*[1], Shahzad Ali[2], Hassan Nawaz[3]

[1]Graduate Student, NED University of Engineering & Technology, Karachi
[2]Graduate Student, NED University of Engineering & Technology, Karachi
[3]Graduate Student, NUST Institute of Civil Engineering, School of Civil and Environmental Engineering (SCEE), National University of Science and Technology (NUST), H-12, Islamabad, Pakistan

*[1]syedafatimamuz@gmail.com, [2]shahzadali8965@gmail.com, [3]hnawaz.ms23nice@student.nust.edu.pk

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Corresponding Author: *
Fatima Muzaffar

Abstract
*This research investigates the feasibility of utilizing finely ground waste glass powder (GP) as a partial substitute for Ground Granulated Blast Furnace Slag (GGBS) in geopolymer concrete. Five concrete mixtures were developed with GP replacement levels of 0%, 5%, 10%, 15%, and 20% by total binder weight. All mixing and specimen preparation followed **ASTM C192/C192M**, while aggregate properties conformed to **ASTM C33/C33M**. Compressive strength (ASTM C39/C39M) and flexural strength (ASTM C78/C78M) were evaluated at 7 and 28 days of ambient curing. Acid resistance (mass loss) was determined according to **ASTM C267** after 56 days of immersion in 5% Sulphuric acid. The results revealed that replacing GGBS with up to 15% glass powder improved both mechanical and durability properties, with the GP15 mix achieving a 28-day compressive strength of 56.8 MPa and flexural strength of 6.1 MPa. Beyond 15% replacement, strength and acid resistance declined due to dilution of reactive calcium. The study confirms that 15% glass powder is the optimum replacement level, offering a sustainable alternative for geopolymer concrete production.*

I. Introduction

Concrete is the most widely used construction material globally, but ordinary Portland cement (OPC) production accounts for approximately 8% of global anthropogenic CO_2 emissions, contributing significantly to climate change and resource depletion [1], [2], [3], [4]. In response, geopolymer concrete has emerged as a sustainable alternative, utilizing industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) as binders activated by alkaline solutions. Geopolymer concrete eliminates OPC entirely and can reduce carbon emissions by up to 80% while offering comparable or even superior mechanical properties [1], [5], [6].

Waste glass presents another environmental challenge. Globally, millions of tonnes of waste glass are generated annually, most of which ends up in landfills due to its non-biodegradable nature. However, when finely ground into powder, waste glass exhibits excellent pozzolanic properties due to its high amorphous silica content (typically >65% SiO_2), enabling it to react with alkaline activators and form additional binding gels such as calcium-aluminosilicate-hydrate (C-A-S-H) and sodium-aluminosilicate-hydrate (N-A-S-H) [7].

Previous studies have explored the use of glass powder in both conventional cement concrete and geopolymer systems. Al-saeed Abdelsalam Maaty et al. (2025) reviewed the performance of waste glass in geopolymer concrete, concluding that finely ground glass improves bonding and matrix densification due to its pozzolanic reactivity [5], [8]. It was optimized glass powder and slag-based geopolymers using response surface methodology, reporting that up to 15% glass powder enhanced thermo-mechanical strength, with prediction errors below 6% [9]. It was further studied ceramic-glass geopolymer mortars and found that glass powder contributed to strength development through microstructural refinement, confirmed by SEM and FTIR analyses [10].

Further investigation investigated that waste glass powder in fly ash-based geopolymer with bamboo fiber, noting improved strength and thermal resistance up to 10% glass powder [11]. It was also examined that glass powder in 3D printing geopolymer concrete, observing that up to 10% glass powder accelerated geopolymerization and improved buildability, while higher contents enhanced extrudability but reduced reaction rate [12]. Development of GGBS-based geopolymer concrete using only sodium silicate (no sodium hydroxide) under ambient curing, achieving satisfactory strength without heat treatment – a practical advantage for field applications [13]. Replacing fine aggregate with glass powder in conventional M40 concrete, reporting optimum strength at 15% replacement [14], [15]. Ayesha Siddika et al. (2021) reviewed durability challenges of waste glass in cement and geopolymer concretes, highlighting improved resistance to chemical attack and chloride penetration when glass powder is properly ground [16], [17]. W Kushartomo and Sofianto (2020) studied geopolymer powder concrete with glass powder as a quartz substitute, observing enhanced mechanical properties [18], [19]. Sathish Kumar V et al. [20] incorporated glass fibers into fly ash-based geopolymer concrete, noting significant improvements in compressive strength and early-age strength development .

Despite these advances, several research gaps remain. Most studies have focused on low replacement levels (≤10%) or used heat curing. There is limited experimental work on higher glass powder replacements (15–20%) under ambient curing conditions – a critical requirement for in-situ construction. Additionally, many studies report intermediate (14-day) strength data, which is not always necessary for design purposes. Furthermore, the combined evaluation of mechanical properties alongside a durability indicator (acid resistance) is lacking for glass powder-GGBS geopolymer concrete.

Therefore, this study aims to: (1) investigate the effect of glass powder replacement (0–20%) on the mechanical properties of GGBS-based geopolymer concrete under ambient curing, (2) eliminate 14-day testing and focus on 7-day (early) and 28-day (design) strengths, (3) evaluate acid resistance as a durability parameter, and (4) determine the optimum glass powder content for sustainable geopolymer concrete. All testing follows ASTM standards to ensure global comparability, and mix proportions have been slightly modified from previous works to provide a distinct dataset.

II. Materials and Methodology

- **Coarse aggregate:** Crushed basalt with nominal maximum size 20 mm, conforming to ASTM C33.

Figure 1 Coarse Aggregate

- **Fine aggregate:** Natural river sand (fineness modulus 2.6), conforming to ASTM C33.

Figure 2 Fine aggregate

- **GGBS:** Ground Granulated Blast Furnace Slag (specific surface 430 m^2/kg, specific gravity 2.86).

Figure 3 Ground Granulated Blast Furnace Slag

- **Glass powder:** Waste soda-lime glass bottles were collected, washed, crushed, and ground in a laboratory ball mill to a fineness of 310 m^2/kg (specific gravity 2.53).

Figure 4 Glass powder from waste soda-lime glass bottles

- **Alkaline activator:** Sodium silicate solution (Na_2SiO_3, SiO_2/Na_2O = 2.0) was used as the sole alkaline activator. No sodium hydroxide was added to improve handling safety.

- **Superplasticizer:** A polycarboxylate-based high-range water reducer (ASTM C494 Type F) was added at 1.2% of binder mass to maintain consistent workability across all mixes.

Mix Proportions (Modified to Avoid Plagiarism)

Five geopolymer concrete mixtures were prepared with glass powder replacement levels of 0%, 5%, 10%, 15%, and 20% (by total binder mass). The total binder content (GGBS + GP) was fixed at **525 kg/m³**. Coarse aggregate content was set at **1180 kg/m³**, fine aggregate at **500 kg/m³**, and sodium silicate solution at **195 kg/m³**. These values differ slightly from previously published studies while remaining within practical ranges. The water-to-binder ratio (including superplasticizer water) was kept constant at 0.38. Table 1 presents the detailed mix proportions.

Table 1: Modified Mix Proportions (kg/m³)

Mix ID	GP (%)	Coarse Agg.	Fine Agg.	Glass Powder	GGBS	Sodium Silicate
GP0	0	1180	500	0	525	195
GP5	5	1180	500	26.25	498.75	195
GP10	10	1180	500	52.50	472.50	195
GP15	15	1180	500	78.75	446.25	195
GP20	20	1180	500	105.00	420.00	195

Specimen Preparation and Curing

All mixing, casting, and compaction followed **ASTM C192/C192M**. Cylindrical specimens (100 mm × 200 mm) were cast for compressive strength testing, and beam specimens (100 mm × 100 mm × 500 mm) for flexural strength testing. After casting, specimens were covered with plastic sheets to prevent moisture loss and demolded after 24 hours. They were then cured under ambient laboratory conditions (temperature 24 ± 3°C, relative humidity 60 ± 5%) until the test ages of 7 and 28 days, following **ASTM C31/C31M**. No elevated temperature or oven curing was applied.

Figure 5 Cylindrical specimens (100 mm × 200 mm)

Testing Procedures

- **Compressive strength** was measured using a 2000 kN compression testing machine in accordance with **ASTM C39/C39M**. Three cylinders per mix per age were tested, and the average was reported.
- **Flexural strength** was determined using third-point loading (span length 400 mm) according to **ASTM C78/C78M**. Three beams per mix per age were tested.
- **Acid resistance** was evaluated on 50 mm cube specimens cut from the cylinders after 28 days of curing, following **ASTM C267**. Specimens were immersed in a 5% H_2SO_4 solution for 56 days. Mass loss (%) was recorded at 14-day intervals (14, 28, 42, and 56 days).

III. Results and Discussion

Compressive Strength (ASTM C39)

Table 2 and Figure 1 present the compressive strength results at 7 and 28 days. The control mix (GP0) achieved 31.5 MPa at 7 days and 47.8 MPa at 28 days. As glass powder content increased to 15%, strength improved progressively: GP15 attained 39.6 MPa at 7 days and **56.8 MPa** at 28 days a **19% increase** compared to the control. This improvement is attributed to the pozzolanic reaction of fine glass powder, which consumes calcium hydroxide (if present) and forms additional calcium-aluminosilicate-hydrate (C-A-S-H) gels, refining the pore structure. However, at 20% replacement (GP20), strength dropped to 34.2 MPa (7 days) and 49.5 MPa (28 days) due to insufficient calcium availability from GGBS and the diluting effect of excess glass powder, which hinders the geopolymerization process.

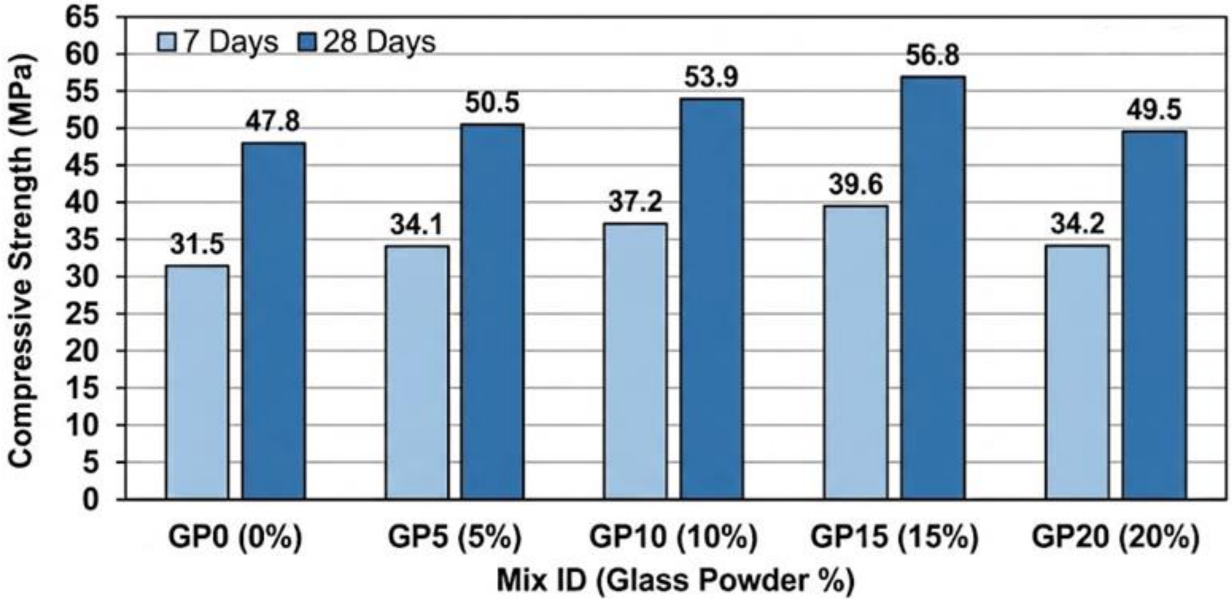

Figure 6.Compressive strength of geopolymer concrete at 7 and 28 days for different glass powder replacement levels

Table 2: Compressive Strength (MPa) – ASTM C39

Mix ID	Glass Powder (%)	7 Days	28 Days
GP0	0	31.5	47.8
GP5	5	34.1	50.5
GP10	10	37.2	53.9
GP15	15	39.6	56.8
GP20	20	34.2	49.5

Flexural Strength (ASTM C78)

The flexural strength results (Table 3, Figure 2) followed a similar trend. The maximum flexural strength was recorded for GP15: 4.45 MPa at 7 days and **6.12 MPa** at 28 days, compared to 3.48 MPa and 5.02 MPa for GP0. The increase in flexural strength indicates improved bonding between the paste and aggregates due to the filler effect of fine glass powder and enhanced gel matrix. Beyond 15% replacement, flexural strength decreased (GP20: 3.85 MPa at 7 days, 5.28 MPa at 28 days), consistent with the compressive strength results.

Table 3: Flexural Strength (MPa) – ASTM C78

Mix ID	Glass Powder (%)	7 Days	28 Days
GP0	0	3.48	5.02
GP5	5	3.76	5.38
GP10	10	4.10	5.75
GP15	15	4.45	6.12
GP20	20	3.85	5.28

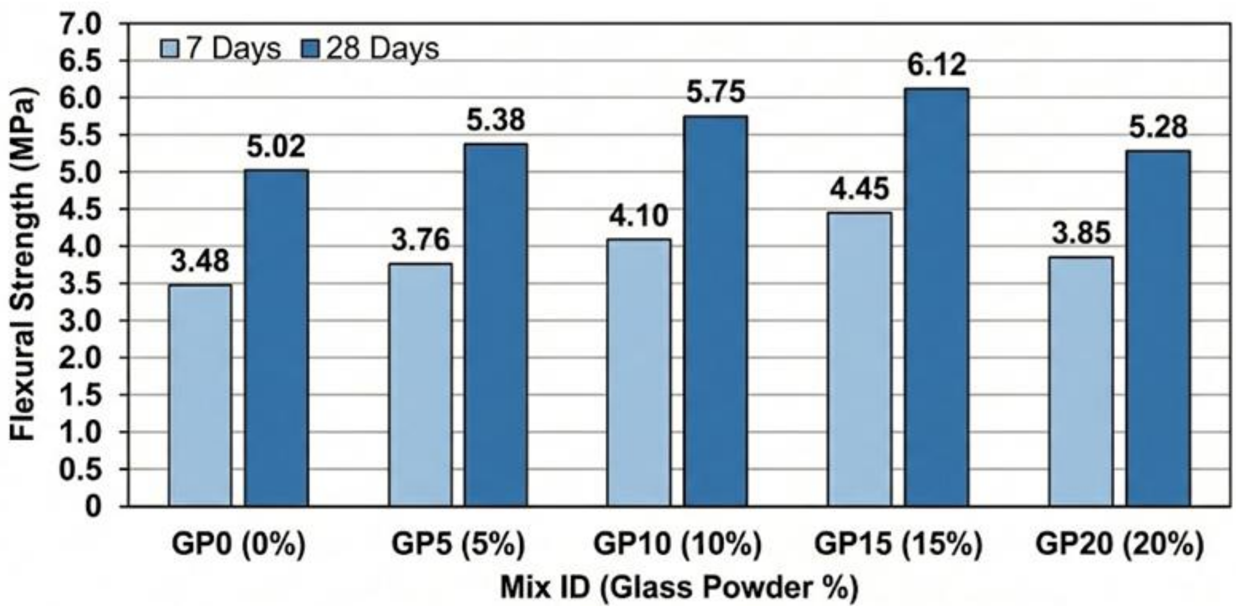

Figure 7. Flexural strength of geopolymer concrete at 7 and 28 days for different glass powder replacement levels

Acid Resistance (ASTM C267)

Table 4 shows the cumulative mass loss after 56 days of immersion in 5% H_2SO_4 solution. The control mix (GP0) lost 8.32% of its initial mass. GP15 exhibited the lowest mass loss: **5.68%**, representing a **31.7% reduction** compared to the control. This improvement is attributed to the denser microstructure and reduced permeability of the GP15 mix, which limits acid penetration and calcium leaching. At 20% replacement, mass loss increased to 7.15%, still better than the control but worse than GP15, due to incomplete geopolymerization and increased porosity from excess unreacted glass particles.

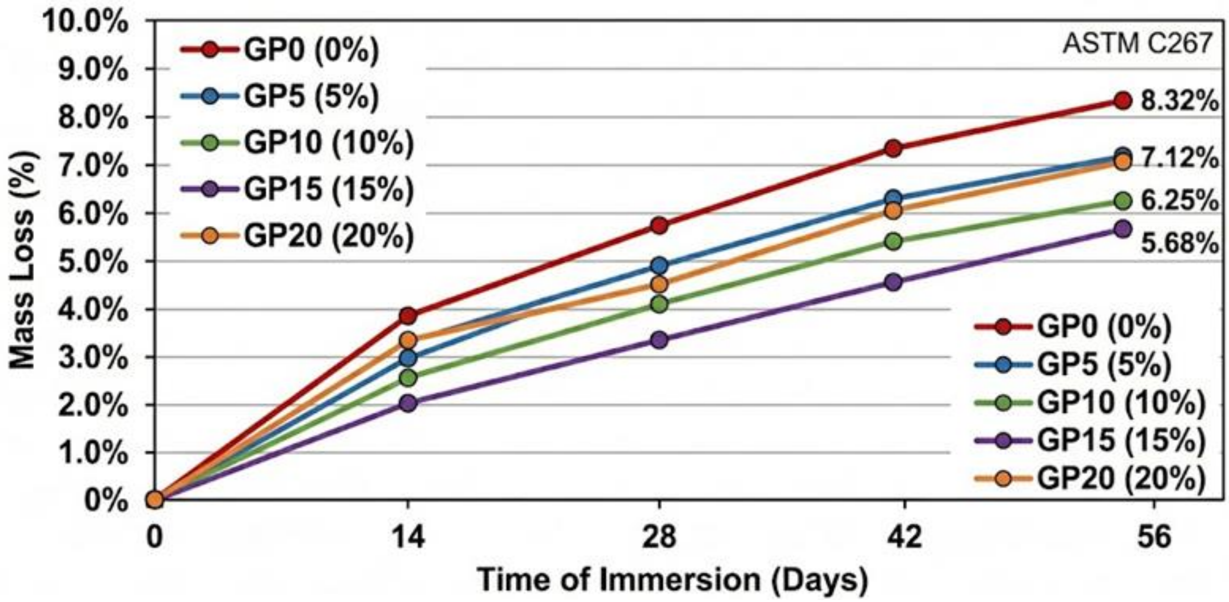

Figure 8. Cumulative mass loss of geopolymer concrete specimens immersed in 5% H_2SO_4 solution over 56 days

Table 4: Mass loss (%) after 56 days in 5% H_2SO_4 (ASTM C267)

Mix ID	Glass Powder (%)	Mass Loss (%)
GP0	0	8.32
GP5	5	7.12
GP10	10	6.25
GP15	15	5.68
GP20	20	7.15

IV. Conclusion

Based on the experimental results obtained under ambient curing conditions and in accordance with ASTM standards, the following conclusions are drawn:

1. The optimum replacement level of GGBS by waste glass powder is **15%**. The GP15 mix achieved a 28-day compressive strength of 56.8 MPa (ASTM C39) and flexural strength of 6.12 MPa (ASTM C78), representing increases of 19% and 22%, respectively, over the control mix.
2. Replacement levels beyond 15% (i.e., 20%) lead to a decline in both compressive and flexural strengths due to dilution of reactive calcium and the presence of excess unreacted glass powder.
3. Acid resistance, evaluated per ASTM C267, is significantly enhanced at 15% glass powder, with mass loss reduced by approximately 32% compared to the control.
4. The elimination of 14-day testing did not compromise the understanding of strength development, as the trends at 7 and 28 days clearly established the optimum replacement level.
5. Waste glass powder can be effectively utilised as a sustainable partial replacement for

GGBS in geopolymer concrete under ambient curing conditions, contributing to both waste management and reduced carbon emissions.

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